

Article

Research on Hydroponic Cultivation Substrates Made from Rice Straw

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Abstract: This study explores the development of a biodegradable hydroponic substrate derived from rice straw, aiming to address environmental sustainability, resource efficiency, and nutritional challenges in agriculture. Traditional non-biodegradable substrates like rockwool have inherent limitations, while the substrates developed herein offer sustainable alternatives by utilizing agricultural waste. This paper details the comprehensive process of converting rice straw into an effective hydroponic substrate through cutting, soaking, defibrating, compressing, and drying. It also evaluates key physical properties such as density, porosity, and permeability. The results indicate that the rice straw substrate meets hydroponic cultivation standards, with a density range of 0.07–0.1 g/cm³, porosity between 88 and 92%, and saturated permeability ranging from 0.02 to 0.08 cm/s, thus demonstrating its potential as a viable substitute for conventional substrates. Scanning electron microscopy (SEM) and SEM-EDS analysis show that the rice straw substrates exhibit a coarse texture and uniform cellulose particle size. The primary elements identified were carbon (C), oxygen (O), aluminum (Al), silicon (Si), and calcium (Ca).

Keywords: biomass; rice straw; hydroponic substrate; rockwool



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1. Introduction

In the early 1930s, Professor William F. Gericke [1] introduced the word “hydroponic” [2] to refer to the practice of growing plants whose roots are suspended in water that contains nutrients and minerals with or without the use of substrates such as vermiculite, coconut coir, perlite, and peat mosses [3]. This system helps address the challenges of climate change and aids in the management of production systems for the efficient utilization of natural resources and the mitigation of malnutrition [4].

It is projected that the global population will be 50% larger than it is today by 2050, with a corresponding doubling of grain demand [5]. Hydroponics presents an alternative method for growing plants to counteract the expected decline in soil fertility and quality due to climate change, natural disasters, and the indiscriminate use of agricultural chemicals. Current hydroponic systems can be categorized into two distinct groups: systems that utilize a substrate, “soilless culture”, and those that operate without one, “water culture”.

Between 1960 and 1970, hydroponic systems utilizing “plastic bed” substrates were initially developed for production, marking Japan’s entry into the commercial cultivation of hydroponically grown crops. Rockwool, a fibrous organic substance produced by the steam blasting and cooling of molten glass, has been commonly used for acoustic insulation and as a synthetic soil for plant growth [6]. Owing to its advantages, such as good aeration, water absorption, water repellency, and affordability, rockwool has been widely used.

However, its life span is approximately 1–2 years. This leads to significant annual rockwool waste generation. Traditional disposal methods such as landfilling and stockpiling are not environmentally friendly solutions. Rockwool, a commonly used synthetic substrate in hydroponic systems, is produced through energy-intensive manufacturing processes, resulting in a significant carbon footprint. Consequently, reducing the reliance on rockwool by developing alternative, biodegradable substrates is a critical step toward sustainable agricultural practices [7,8].

As stated by the reports of FAO 2022 [9], world rice production of approximately 787 million tons of rice per annum has occurred. Global consumption reached approximately 520.4 million metric tons in 2022/2023. Especially, Asia accounts for 74% of the global rice consumption [10], and rice production generates an equivalent amount of rice straw. Rice cultivation has been prevalent in Japan since the Jomon period. According to investigations by the Ministry of Agriculture, Forestry and Fisheries (MAFF) [11], the annual rice straw production in Japan is approximately 7.5 million tons, with only 10% used for livestock feed, whereas the remaining 90% is typically incinerated or landfilled [12]. Rice straw is characterized by a slow decomposition rate, which can pose challenges in agricultural systems, particularly in intensive cropping systems with short intervals between crops. As a result, some farmers avoid incorporating rice straw into the soil due to the time required for its breakdown. Furthermore, the slow decomposition of rice straw can disrupt nutrient cycling and soil fertility, potentially leading to nutrient imbalances if not properly managed [13,14]. To address these challenges, some farmers resort to straw burning, a common practice that releases pollutants such as PM_{2.5}, SO₂, CO, NH₃, VOC, and NO_x [15]. This practice significantly contributes to haze and smog formation, particularly during harvest periods in China [16,17]. Therefore, reutilizing rice straw has become increasingly crucial.

The objective of this study was to develop a biodegradable growing substrate for use in hydroponic systems as a sustainable alternative to rockwool. In this context, rice straw presents significant potential for greenhouse applications. By repurposing rice straw into a substrate, this approach not only addresses the need for eco-friendly growing media but also provides an alternative to open-field burning, thereby reducing the release of environmental pollutants such as PM_{2.5}, SO₂, and CO₂.

2. Materials and Methods

2.1. Basic Principle

Chemical composition analyses [18,19] of fourteen japonica-type rice (*Oryza sativa* L.) straws revealed that the crude protein content ranged from 3.0% to 3.8%, the acid detergent fiber (ADF) content ranged from 41.4% to 45.2%, and the acid detergent lignin (ADL) content ranged from 4.8% to 5.6% on a dry matter basis. In addition, rice straw was generally composed of 28–45% α -cellulose, 12–32% hemicellulose, 23–28% pentosans, and 5–24% lignin, with the major components defining the composition of any lignocellulosic biomass. These values indicate the nutritional and structural composition of the rice straw. Although the mean ADF value of various rice stems was slightly greater than that of leaf blades and leaf sheaths, the difference among straw parts was not considered in this experiment. The predominant components of rice straw, cellulose and hemicellulose, are crucial for fiber formation and contribute significantly to the structural integrity of the substrate. Depending on the constituent sugars of the polysaccharides, we can differentiate between cellulose, whose structural unit is glucose, and hemicelluloses, which are formed by different monosaccharides. Cellulose is an abundant, renewable, non-toxic, and relatively cheap biopolymer found in nature, but it is also produced as waste in different industrial sectors.

Rice straw substrate consists of cellulose fibers that are bonded together through hydrogen bonds. According to Hubbe [20], cellulose and hemicellulose, the primary components of these fibers, are adorned with hydroxyl groups. The oxygen atoms in these hydroxyl groups can form hydrogen bonds with hydrogen atoms on adjacent fibers or with water molecules. During the drying process of the bioboard, some fiber-to-fiber hydrogen bonds replace the fiber-to-water hydrogen bonds, enhancing the structural stability of the substrate.

The exploitation of hydrogen bonding in the production of this substrate is innovative. Pressure is applied during the process to expel water from the rice straw fibers, while maintaining a moderate temperature helps evaporate water molecules between the cellulose fibers [21]. This method ensures that the fibers are tightly bonded, resulting in a durable and stable substrate. The combination of pressure and controlled temperature conditions is critical in achieving the desired properties of the rice straw substrate, making it a viable alternative for various applications, including hydroponic cultivation.

2.2. Manufacture of Substrates

Koshihikari rice (*Oryza sativa* ssp. *japonica*) was used in this study, which produces the best rice in Japan and is one of the varieties with the greatest production volume in the country. The planting date for Koshihikari rice in Mie Prefecture was in early May, and Koshihikari rice was harvested at the beginning of September before the typhoon season according to the practices of the Japanese Agricultural Cooperatives (JA) [22]. The process for producing rice straw substrates can generally be divided into five steps, as shown in the flow chart in Figure 1.



Figure 1. Production flow chart for rice straw substrate.

- Pretreatment

After harvesting, the rice grains were removed. The stems and leaves were left in a ventilated storage area and air-dried for one month.

- Cutting

To separate the fibers, the dried rice straw was cut into lengths of less than 1 cm via the shredder machine SHINKOWA, SU-16 (1-5PS 750~900 rpm). A speed of 900 rpm was applied during this process.

- Soaking

The cut rice straw was soaked in water at room temperature for 72 h [23]. During the soaking process, the rice straw fiber bundles absorbed moisture. It was easier to soften fiber bundles under humid conditions than to destroy the structure of the lignocellulose fibers in a dry state. The soaking process was performed in preparation for the fiberization of rice straw. This process softens the fibers and improves the conditions for efficiently defibrating the rice straw fibers into a pulp.

- Defibrating

The rice straw was transformed into a pulp through a defibrating process involving the use of an atmospheric refiner (Model A Beatfiner. Satomi. Corp., Shizuoka, Japan). The motor capacity was 11 kW × 4p-200, 60 Hz, and the rotational speed was 1750 rpm (60 Hz). The maximum flux was 0.05–0.1 m³/min. The required air pressure was 0.6 MPa. The grinding part included a conical cutter with blades. The dimensions of the cutter were

2.5 mm $\times$ 3.0 mm $\times$ 8° (blade width $\times$ slot width $\times$ blade angle). The process began with the introduction of rice straw and water from a 1 L cube tank into the beat refiner. Rice straw was then milled by the teeth plates of the refiner to separate celluloses and lignin. The milled rice straw was returned to the tank to repeat the process until all the rice straw was converted into rice straw pulp. Fiberization of the rice straw at atmospheric pressure was carried out by passing the damp cut straw along with running water through the rotating blades of the refiner. During the grinding process, the rice straw matrix exhibits high porosity. The fiber bundles were fiberized by milling. To achieve an optimal balance between retaining fiber bundles and decomposing individual fibers measuring less than 2.0 mm [24], it is crucial to ensure that not all fibers remain as thick bundles. Thick fiber bundles may exhibit weaker hydrophilic properties, which can affect the overall performance of the substrate. Therefore, during the initial decomposition phase, the decomposition time for coarse fibers is kept relatively short. A sieve with apertures greater than 5 mm is used to collect these coarse fibers.

Subsequently, finer fibers are separated using a sieve with apertures less than 2.0 mm. This step ensures that the finer fibers are adequately isolated from the coarser ones. Finally, the finer and coarse fibers are mixed in a specific ratio of 2:8. This mixture ratio is designed to optimize the structural integrity and hydrophilic properties of the rice straw substrate, ensuring that it maintains high porosity while also providing the necessary balance between fiber retention and decomposition.

- **Molding**

A mold for shaping the substrate was meticulously assembled using a stainless-steel cuboid case with dimensions of 70 mm $\times$ 70 mm $\times$ 100 mm. These dimensions were selected based on preliminary trials conducted by team members to evaluate the performance of various substrate sizes. The chosen size demonstrated optimal porosity, water retention, and aeration. The mold included a plate with a centrally located handle and a metal mesh designed to prevent the raw material from adhering to the plate. The assembly process of the mold is illustrated in Figure 2a. Initially, the plate with the handle, as shown in Figure 2b, was placed at the bottom of the mold. Subsequently, the mold was filled with rice straw pulp. Once the mold was adequately filled, a metal mesh was added, as depicted in Figure 2c, followed by the placement of a cover and a weight.

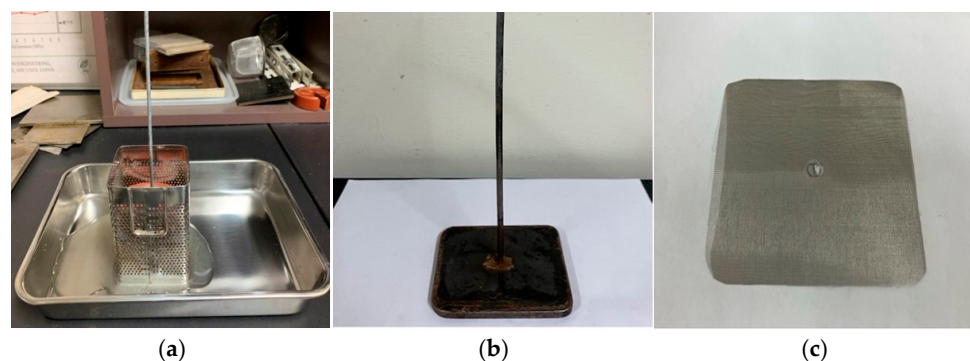


Figure 2. Accessories for the molding process: (a) a metal mold, (b) a plate with a handle, and (c) a metal mesh.

In general, the weight applied was converted into pressure units for precise calculations. Tweezers were employed to carefully add the metal mesh, cover, and weights to avoid exerting additional pressure during the pulp molding process. Additionally, the inner walls of the mold case were equipped with meshes to facilitate the squeezing of water from the pulp through the application of varying pressures. Figure 3 illustrates the molding

process in detail: the plate with the handle was first inserted, followed by the placement of a metal mesh on the plate and the installation of a square mesh wall, and finally, the rice straw pulp was poured into the mold case. Three different types of weights were then placed on the cover to ensure a uniform pressure distribution.

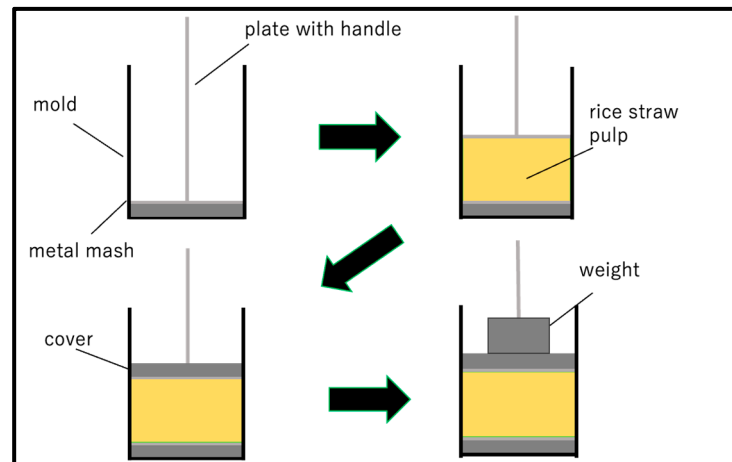


Figure 3. Flow chart of the molding process.

The drying temperature was meticulously set to 110 °C for a duration of 24 h using a thermostat to ensure proper sterilization. This specific drying temperature of 110 °C was selected as the optimal experimental condition to prevent the thermal decomposition of cellulose. The maximum temperature within the mold containing the samples was reached within 8 to 10 min, ensuring efficient drying.

In the text below, “rice straw substrate” is abbreviated as “RS substrate”. Based on the experimental conditions outlined in Table 1, three types of RS substrates were produced, each subjected to one of three pressures: 416 Pa, 1216 Pa, and 2016 Pa. The pressure levels of 416 Pa, 1216 Pa, and 2016 Pa were selected based on practical ranges for compressing rice straw into hydroponic substrates, ensuring a high porosity value above 85%. These levels were also informed by results from preliminary trials. Lower pressure (416 Pa) was tested to evaluate the minimum compaction required, while higher pressure (2016 Pa) assessed the impact of increased compaction on substrate properties such as porosity and water retention. The intermediate pressure (1216 Pa) provided a comparative baseline between the extremes. Under each pressure condition, two samples were produced, resulting in a total of six samples. These samples were designated as RS-A1, RS-A2, RS-B1, RS-B2, RS-C1, and RS-C2.

Table 1. RS substrate molding conditions.

Samples No.	Pressure (Pa)	Rice Straw Fiber Length (mm)	Drying Temperature (°C)	Drying Duration (h)
RS-A1, RS-A2	416	0~5.6	110	24
RS-B1, RS-B2	1216	0~5.6	110	24
RS-C1, RS-C2	2016	0~5.6	110	24

The prepared RS-A1 substrate is depicted in Figure 4. Upon examining the appearance of RS-A1, it was observed that the fibers of the rice straw were firmly combined, indicating successful substrate formation. However, the edges of the four sides were not smooth, and the surface and bottom also exhibited irregularities. It is possible that the mesh wall on the inside might have dislodged when the substrate was removed from the mold, contributing

to these imperfections. Additionally, a hole was present on the surface of the substrate, intended for sowing purposes.



Figure 4. Complete rice straw substrate.

2.3. Density and Porosity

The dimensions of the RS substrates were measured at nine points in terms of length, width, and net weight. The thickness was measured at nine points, as shown in Figure 5. The average value of the thickness was calculated.

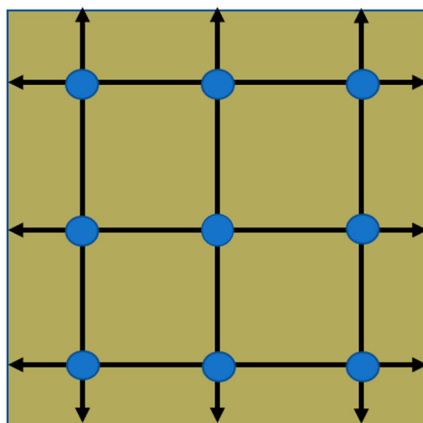


Figure 5. Dimensional measurement of the RS substrate.

Porosity determination: Previous studies of rice straw bioboards have been conducted [23], in which the density of the rice straw bioboards was 0.87 g/cm^3 . In this study, the rice straw bioboard was assumed to be solid, and V_2 was the volume of the rice straw bioboard with dimensions of $100 \text{ mm} \times 100 \text{ mm} \times 1 \text{ mm}$, as shown in Figure 6. Using Formulas (1) and (2), the porosity of the RS substrates could be obtained.

$$V_2 = \frac{W}{\rho} \quad (1)$$

$$f = \frac{V_1 - V_2}{V_1} \quad (2)$$

where the following definitions hold:

f : porosity;

V_1 : volume (cm^3);

V_2 : solid volume (cm^3);

W : fiber weight (g);
 ρ : rice straw density (g/cm³).

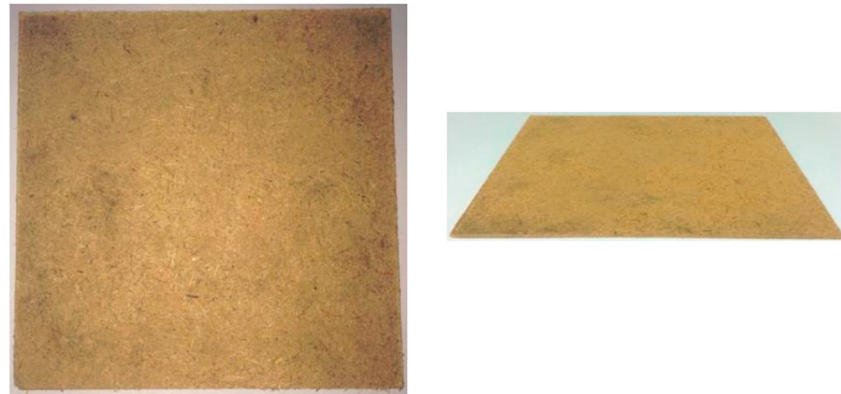


Figure 6. A piece of rice straw bioboard.

2.4. Observation by Scanning Electron Microscopy (SEM)

Firstly, scanning electron microscopy (SEM) (JSM-IT200; Japan Electron Optics Laboratory, Tokyo, Japan) was utilized to examine the side surface of substrate specimens from RS-A1 and RS-C1 at a magnification of 30 $\times$. Additionally, the fracture surface of the substrate, after internal cutting from samples from RS-A2, RS-B2, and RS-C2 at a magnification of 100 $\times$, was observed. All specimens were coated with a 6:4 aurum–palladium alloy using an ion sputter coater (E1010; Hitachi, Tokyo, Japan). A field emission SIM was employed for detailed microscopic analysis.

To analyze the elemental composition of the substrate, Energy-Dispersive X-ray Spectroscopy (EDS) was conducted using the detector integrated with the scanning electron microscope (SEM). Specific areas of the RS samples were selected from the SEM images for EDS analysis. The analysis was performed at a magnification of 120 $\times$ under high vacuum conditions, with a secondary electron detector (SED) signal, an accelerating voltage of 15 kV, and a working distance (WD) of 10 mm, as shown in Figure 7. The characteristic X-rays emitted by the elements in the RS-A2 sample were detected and used to identify and quantify its elemental composition.

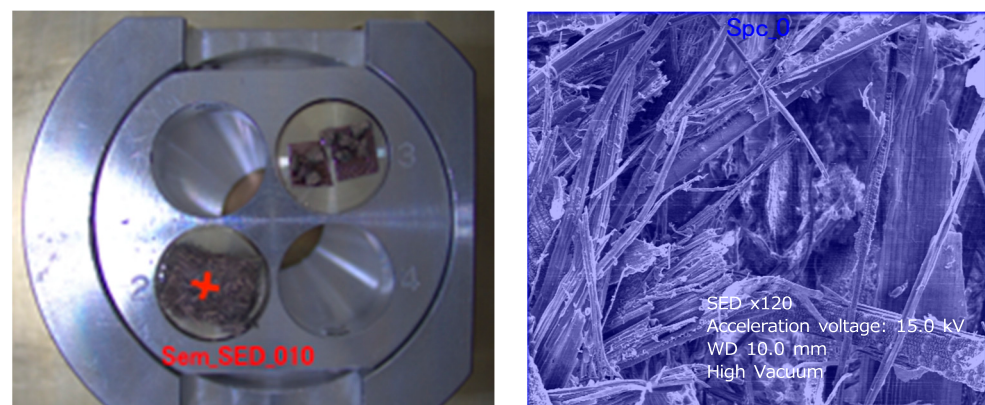


Figure 7. Analysis areas of sample by SEM-EDS.

2.5. Constant Head Permeameter Test

In this study, a constant head permeameter test was conducted on the RS substrate. Permeability is an indicator obtained by determining the permeability coefficient, which represents the amount and degree of water movement within the RS substrate. In hydroponic cultivation, the nutrient mixture constantly moves within the substrate, and by

understanding this movement, we can investigate the characteristics and properties of the substrate. For example, in a substrate with a low permeability coefficient, there is a concern that the proportion of the liquid phase increases, leading to a relative decrease in the proportion of the vapor phase and potentially causing insufficient oxygen supply to plants. Additionally, there is a possibility of uneven nutrient solution distribution between the upper and lower layers of the substrate. Therefore, permeability tests were conducted to examine the specific properties of the RS substrate.

2.5.1. Assembled Permeameter Apparatus

The permeameter apparatus consisted of two distinct chambers. A schematic representation of the apparatus is provided in Figure 8a, while the fully assembled permeameter apparatus is depicted in Figure 8b.

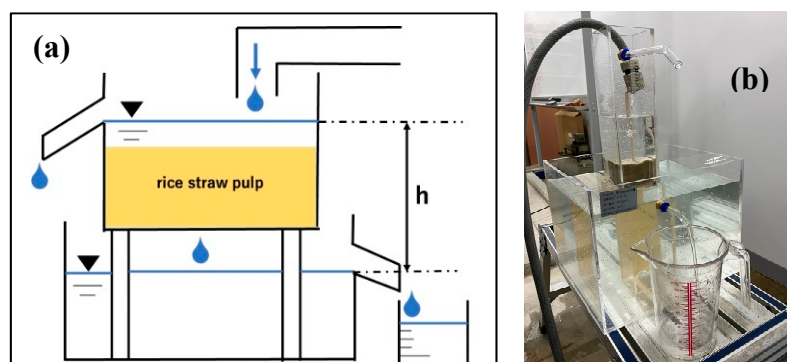


Figure 8. Constant head permeameter test: (a) diagram and (b) assembled permeameter apparatus.

The rice straw (RS) substrate was positioned within the top chamber. Water was continuously supplied to this top chamber, also referred to as the input chamber, at a constant head through a water pipe. The effluent water was subsequently collected in the bottom chamber, known as the output chamber. During this overflow process, the volume of water flowing out per unit time from the output chamber was meticulously measured to determine the substrate's permeability during the test.

The flow rate of water passing through each substrate sample was measured over a period of 20 s using a timer and a measuring cup. This measurement process was repeated five times for each substrate tested to ensure accuracy and reliability. Additionally, six samples of the RS substrate were utilized in the permeability test to provide a comprehensive assessment of the substrate's permeability characteristics.

2.5.2. Calculation of the Saturated Permeability

The saturated permeability was calculated via Formula (3):

$$K = \frac{Q \cdot L}{A \cdot h} \quad (3)$$

where the following definitions hold:

K : saturated permeability (cm/s);

Q : flow rate of water passing through the substrate per unit time (cm³/s);

L : length of the flow path (cm);

A : cross-sectional area of the substrate (cm²);

h : hydraulic head difference across the substrate (cm).

3. Results and Discussion

3.1. Density and Porosity of the Rice Straw Substrate

A cultivation substrate made from rice straw shown in Figure 4 was successfully developed using our original manufacturing processes. Among these, defibration proved to be the most critical step. This process breaks rice straw into smaller fibers, significantly increasing the surface area and partially disrupting the tightly bound lignocellulosic matrix. Such disruption exposes more hydroxyl groups (-OH) in cellulose, thereby enhancing hydrogen bonding potential [25]. While rice straw is a readily available raw material, the production of substrates involves processes such as defibration and compaction, which consume energy and resources. Future research will aim to quantify these inputs and explore opportunities for optimizing production efficiency to minimize the environmental impact [26].

The calculated density and porosity are shown in Figure 9 and Table 2, respectively. The average density of RS-A1 and RS-A2 was 0.07 g/cm^3 , that of RS-B1 and RS-B2 was 0.09 g/cm^3 , and that of RS-C1 and RS-C2 was 0.10 g/cm^3 . On the other hand, the densities of rockwools (a) and (b) were in the range of $0.04\text{--}0.1 \text{ g/cm}^3$ [27] and were close to those of the RS substrate.

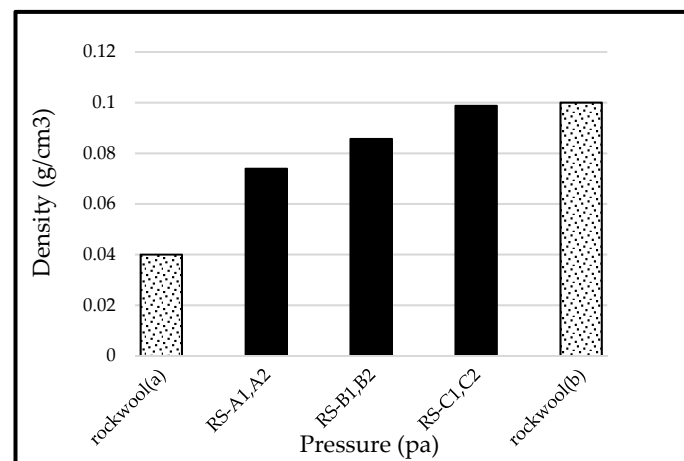


Figure 9. The density of the substrate under each loading pressure.

Table 2. Porosity of the RS, rockwool, and coir substrates.

Samples	Pressure (Pa)	Porosity (%)
Rockwool	-	95 ± 5 [23]
Coir	-	91 ± 5 [23]
RS-A1	416	91
RS-A2	416	92
RS-B1	1216	91
RS-B2	1216	90
RS-C1	2016	88
RS-C2	2016	89

The porosity of the rockwool substrate was in the range of $95 \pm 5\%$, indicating a highly porous structure. In contrast, the RS substrate produced in this study exhibited a maximum porosity value of 92%, which, although slightly lower than that of rockwool, still demonstrated significant porosity. According to previous research, the required porosity for hydroponic cultivation media is 85% or greater [28]. The substrates produced in this study consistently met this criterion under all tested conditions, ensuring their suitability for hydroponic applications.

Furthermore, the porosity of the coir substrate, derived from coconut and commonly used as a hydroponic cultivation medium, was approximately $91 \pm 5\%$. The porosity range for the RS substrates was between 88% and 92%, indicating that the RS substrates achieved porosities comparable to those of both rockwool and coir substrates [29]. This similarity in porosity values suggests that RS substrates could serve as viable alternatives to traditional hydroponic substrates, offering comparable performance in terms of porosity.

Therefore, the RS substrates not only met the essential porosity requirements for hydroponic cultivation but also demonstrated porosity levels that were closely aligned with those of widely used substrates such as rockwool and coir. This finding underscores the potential of RS substrates as effective and sustainable options for hydroponic cultivation systems.

Currently, rockwool substrates are used for approximately one year or longer. In comparison, the rice straw substrate demonstrated greater water retention and nutrient retention in this study, suggesting potential benefits. The defibrated rice straw exhibits a more porous structure, which is essential for water retention and aeration in hydroponic or substrate-based cultivation systems. This improved porosity not only supports plant root health but also increases the substrate's overall water-holding capacity, making it a highly effective medium for plant growth. However, substrates with high water retention and nutrient retention are prone to significant weight fluctuations. Such fluctuations in pore structure can affect the substrate's permeability; long-term studies on the robustness and stability of the rice straw substrate are crucial for its practical application.

3.2. Microstructural Properties of RS

In addition, the surface and cross-sectional morphology of the RS matrix were examined using a scanning electron microscope (SEM). As shown in Figure 10, at a magnification of 30x, it was observed that the cellulose particles on the (a) RS-A1 and (b) RS-C1 surface exhibited a relatively uniform size with a coarse texture, which contributes to maintaining the structural integrity and durability of the RS. Moreover, surface roughness increases the adhesion of nutrient solution to the substrate surface, promoting nutrient availability. The side view revealed bundled cellulose fibers with internal pores. The SEM analysis showed a uniform arrangement of fibers, which contributes to structural stability and supports root penetration, ensuring better access to water and nutrients [30].

In the 100 $\times$ magnified images of the interior of RS-A2, RA-B2, and RA-C2 ((c), (d), and (e)) pronounced voids were observed alongside thick cellulose bundles, indicating a relatively high porosity in the rice straw substrate. This high porosity, coupled with an interconnected pore structure, plays a critical role in maintaining water retention and facilitating capillary action. These characteristics ensure the even distribution of nutrient solutions throughout the substrate, thereby enhancing nutrient availability to plant roots [31].

From the three specimens RS-A2, B2, and C2 prepared under varying pressures, it is observed that their internal structures exhibit a high degree of similarity. Specifically, all samples consist of coarse cellulose bundles intertwined with fine cellulose fibers and contain internal pores. However, as illustrated in figures (c) and (d), the porosity is more pronounced compared to figure e, where the fibers are densely packed. This observation corroborates the conclusion that an increase in external pressure results in a decrease in internal porosity.

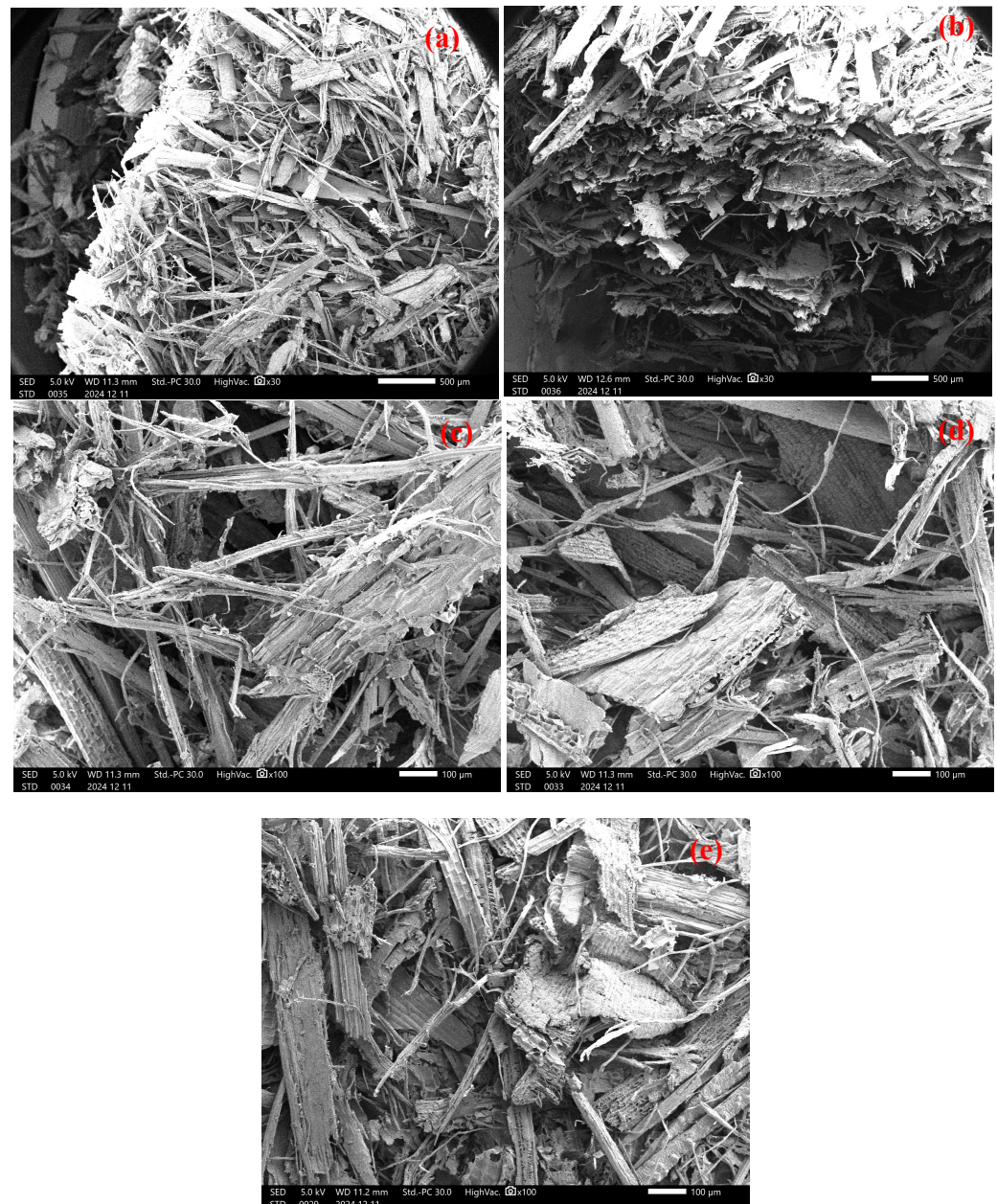


Figure 10. SEM images of surface and cross-sectional structures of RS, (a) RS-A1, (b) RS-C1; images of internal structures of RS, (c) RS-A2, (d) RS-B2, (e) RS-C2.

3.2.1. Elemental Composition of RS

The Energy-Dispersive X-ray Spectroscopy (EDS) analysis provided detailed insights into the elemental composition of the rice straw (RS) substrate. The primary elements identified were carbon (C), oxygen (O), aluminum (Al), silicon (Si), calcium (Ca), and gold (Au), as shown in Table 3. The high presence of carbon (C) and oxygen (O) reflects the organic nature of rice straw, predominantly composed of cellulose, hemicellulose, and lignin. These elements are critical for the structural framework of the substrate and contribute to its biodegradability and compatibility with hydroponic systems. This indicates the suitability of the substrate for plant root systems due to its organic structure and biodegradability. The detection of aluminum (Al) and silicon (Si) is consistent with the presence of silica and other mineral residues typically found in rice straw. Silicon, in particular, is a significant component of rice husks and contributes to the rigidity of the substrate, which may influence its structural stability. Calcium (Ca) may originate from

residual agricultural inputs or natural mineral content. Calcium can play a role in nutrient buffering and root health in hydroponic systems.

Table 3. Elemental composition of RS determined by EDS analysis.

	C	O	Al	Si	Ca	Au	Total
Spc_001	42.93	34.8	0.48	4.67	0.34	16.77	100
	Atom/Mol %						

3.2.2. The X-Ray Spectrum Analysis

The X-ray spectrum confirmed the elemental composition of the substrate, as shown in Figure 11. Peaks corresponding to carbon and oxygen were dominant, consistent with the organic matrix of rice straw. Smaller peaks for aluminum, silicon, and calcium align with the expected trace mineral content. The gold peak was prominent but excluded from substrate composition analysis, as it originated from the sample coating.

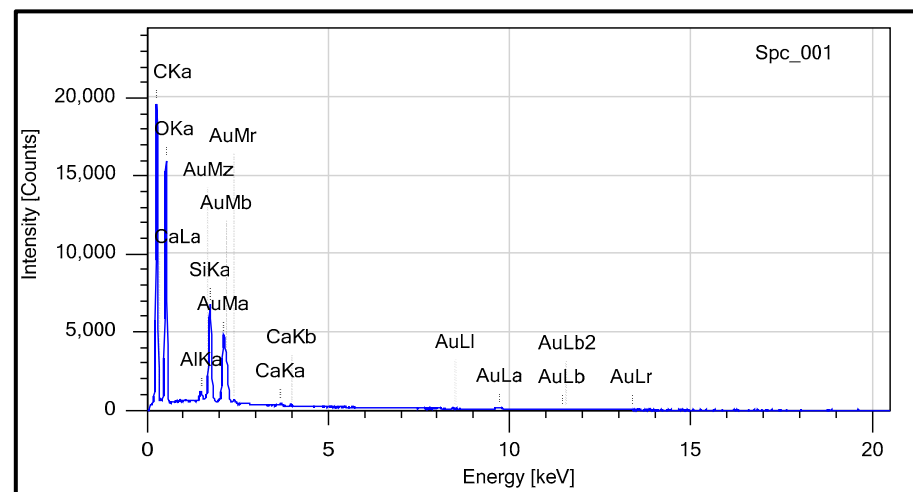


Figure 11. X-ray spectrum analysis.

3.3. Constant Head Permeameter Test

The RS substrate was saturated with water during the permeability tests. Figure 12 illustrates the relationship between porosity and saturated permeability. The saturated permeability of each sample was measured five times to ensure accuracy and reliability. The permeability range of 0.03 cm/s to 0.07 cm/s observed in this study aligns with the functional requirements for hydroponic cultivation systems. Substrates within this range facilitate balanced water movement, allowing for effective aeration and nutrient distribution while preventing waterlogging. Specifically, the lower limit (0.03 cm/s) supports water retention, ensuring a steady supply of nutrients to plants with high water requirements. Conversely, the upper limit (0.07 cm/s) enhances drainage, mitigating the risk of root hypoxia and promoting healthy root development in oxygen-sensitive crops. This balance is essential for maintaining optimal hydroponic conditions and maximizing plant growth and yield. Substrates with total porosity exceeding 85% are often deemed ideal for hydroponics due to their ability to retain sufficient moisture while facilitating proper aeration [29]. These findings indirectly support the significance of the observed permeability range in this study.

These results indicate that the RS substrates exhibited properties similar to those of sandy soil. Based on past studies [32], it is known that the saturated permeability suitable for cultivation is 0.011 cm/s. In contrast, the saturated permeability of rockwool is 0.45 cm/s [33], a value that the RS substrates did not achieve. The RS substrates demonstrated lower permeability compared to the rockwool substrate. However, this lower

permeability suggests that the RS substrates may possess greater water retention and nutrient retention capabilities than the rockwool substrate. If this is the case, it implies that stable absorption and release of nutrients can occur between the substrate and the roots of cultivated plants, potentially enhancing plant growth and health.

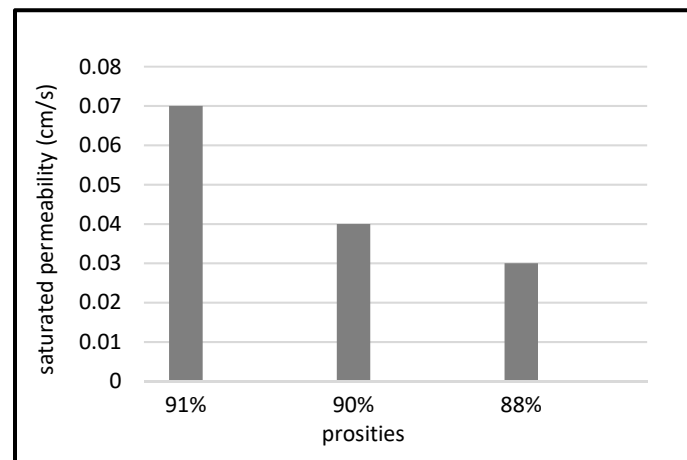


Figure 12. Relationship between saturated permeability and porosity.

Additionally, the findings indicate that RS substrates demonstrate the ability to withstand multiple irrigation cycles and exhibit superior water and nutrient retention capacities compared to rockwool. These attributes position RS substrates as a promising alternative for hydroponic cultivation, offering significant advantages in water and nutrient management. On the other hand, this study does not include direct comparative data with widely used commercial substrates, such as rockwool, under controlled cultivation trials. While the physical and preliminary chemical properties of RS substrates highlight their potential as viable alternatives, their performance in practical applications has yet to be thoroughly validated.

Future research should focus on conducting controlled side-by-side comparisons of plant growth metrics (e.g., biomass, yield, nutrient uptake) and substrate functionality (e.g., water retention, nutrient availability) between RS substrates and established commercial options. Such studies are essential to comprehensively assess the practical benefits and limitations of RS substrates in hydroponic systems, ultimately determining their feasibility and sustainability as a replacement for conventional substrates.

3.4. Relationship Between Porosity and Saturated Permeability

Figure 13 illustrates the relationship between porosity and saturated permeability as measured in this study. The coefficient of determination (R^2) was found to be 0.9372, indicating a strong correlation and that the data fit the regression line well. This high coefficient of determination suggests that the shape and distribution of large pores significantly influenced the saturated permeability of the substrate.

Water movement during saturation is considered to occur primarily through large pores [34]. Large pores offer less resistance to water flow, facilitating continuous water movement. Furthermore, the substrates produced in this study tended to have a lower density and higher porosity than currently used substrates. Therefore, substrates with higher porosities are presumed to have a greater proportion of the vapor phase.

Considering these points, it can be inferred that the substrates with higher porosities produced in this study tended to have relatively large pores rather than fine pores. Additionally, the presence of such large pores distributed throughout the substrate likely

provided pathways for water movement, enhancing permeability and ultimately impacting the saturated permeability of the substrates.

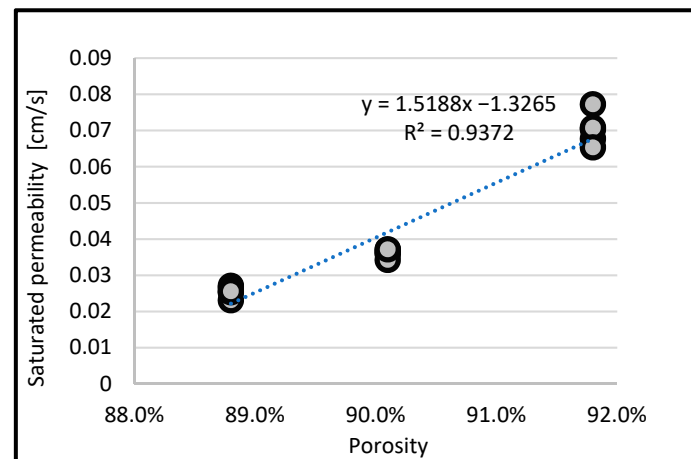


Figure 13. Relationship between porosity and saturated permeability.

4. Conclusions

In this study, we successfully produced a biodegradable substrate made from rice straw as the raw material without the use of chemical additives. SEM analysis revealed that the RS substrates maintained a coarse texture and a uniform cellulose particle size. Additionally, X-ray spectrum analysis identified the primary elements including carbon (C), oxygen (O), aluminum (Al), silicon (Si), and calcium (Ca). These elements highlight the organic and mineral composition of RS substrates, which may influence their physical properties and suitability for hydroponic applications. The density of the RS substrates ranged from 0.07 g/cm³ to 0.10 g/cm³. The produced substrates had porosities ranging from 88% to 92%, meeting the requirement of 85% or higher for a cultivation substrate. Furthermore, the saturated permeability ranged from 0.03 to 0.07 cm/s, meeting the requirement of 0.01 to 1 cm/s for hydroponic growth media. Therefore, it can be concluded that the substrate made from rice straw possesses the necessary physical characteristics for hydroponic cultivation. Finally, the coefficient of determination between the porosity and saturated permeability was 0.9372, indicating that the data fit the regression line well. This study highlights the potential of RS substrates but acknowledges the lack of direct comparisons with commercial options like rockwool. Future research should prioritize cultivation trials, durability assessments, and a comprehensive analysis of chemical properties such as cation exchange capacity (CEC) and pH stability to validate their practical performance.

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